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BEAM COMMISSIONING OF C-ADS INJECTOR-I RFQ ACCELERATOR*

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Abstract

The C-ADS accelerator is a CW (Continuous-Wave) proton linac with 1.5 GeV in beam energy, 10 mA in beam current, and 15 MW in beam power. C-ADS Injector-I accelerator is a 10-mA 10-MeV CW proton linac, which uses a 3.2-MeV normal conducting 4-Vane RFQ and superconducting single-spoke cavities for accelerating. The frequency of RFQ accelerator is 325 MHz. The test stand composed of an ECR ion source, LEBT, RFQ, MEBT and beam dump have been installed and the first stage of beam commissioning have been finished at IHEP in 2014 mid-year. At 90% duty factor, we got 11 mA proton beam at RFQ exit with 90% beam transmission efficiency, while 95% beam transmission efficiency at 70% duty factor. The energy after RFQ was measured by TOF method with FCTs. The transverse emittance measured by double-slits emittance meter was 0.135 π mm-mrad, which of detailed data analysis will be presented in this paper.

INTRODUCTION

The ADS project in China (C-ADS) is a strategic plan to solve the nuclear waste problem and the resource problem for nuclear power plants in China. For the C-ADS accelerator that is a CW proton linac with the proton beam of energy 1.5 GeV and current 10 mA [1]. The C-ADS accelerator uses superconducting acceleration structures, except for the RFQs and is composed of two major accelerating parts: the injector and the main linac. The rf frequencies for the main linac have been chosen as 325 MHz for the spoke cavity sections and 650 MHz for the elliptical cavity sections. However, two different designs employing different rf frequencies are pursued for the low-energy part of less than 10 MeV, namely, injectors in the technical developing phase, with 325 MHz for Injector Scheme-I [2] and 162.5 MHz for Injector Scheme-II.

For the first phase, the project goal is to build a CW proton linac of 25 MeV. The first phase itself will be executed progressively in several steps, with the first step to build two 5-MeV test stands of different front-end designs. Before the test stands of superconducting cavities, we have finished the first stage beam commissioning of the injector-I RFQ accelerator (Table 1), which composed of an ECR ion source, LEBT, RFQ, MEBT and beam dump line. There is an ACCT at the entrance of RFQ and a DCCT at the middle part of MEBT for transmission measurement, FCTs for energy measurement and double-slit for emittance measurement at the MEBT. Detailed analysis will be presented in this paper.

Table 1: Main RFQ design Parameters of Injector-I

Parameters	Value
RF Frequency (MHz)	325
Injection/Output energy (MeV)	0.035/3.2
Pulsed beam current (mA)	15
Beam duty factor	100%
Inter-vane voltage V (kV)	55
Average bore radius r0 (mm)	2.775
Maximum surface field (MV/m)	28.88 (1.62Kilp.)
Cavity power dissipation (kW)	272.94 (1.4*$P_{SUPERFISH}$)
Vane length (cm)	467.75

EXPERIMENTAL APPARATUS

The layout of the test stand is shown in Fig. 1. A 2.45 GHz electron cyclotron resonance (ECR) ion source was installed for the RFQ testing. The extraction energy is 35 keV and the typical pressure was 7.5×10^{-4} Pa. The low energy beam transport (LEBT) is equipped with two

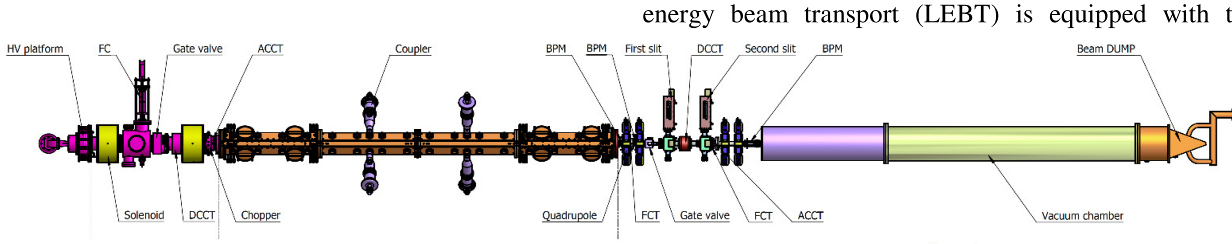

Figure 1: Layout of the test stand.

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solenoid magnets, and the space charge neutralization effect is also considered. The beam current injected to the RFQ is measured using a movable Faraday cup (FC) or an ACCT at the exit of LEBT. The length of the LEBT is 1670 mm. Beam chopper are installed at the exit of LEBT to avoid destroying the space charge neutralization effect. Beam chopping is very important for the commissioning of the C-ADS linac, which one increases the beam duty factor form very low to 100% step by step. The pulse width is form 20 us to CW. Fig.2 shows a photograph of the LEBT and RFQ installed in the test stand. The RFQ have very complicated cooling system to ensure the CW operation and the water flow in each channel runs parallel from the low-energy end to the high energy end.

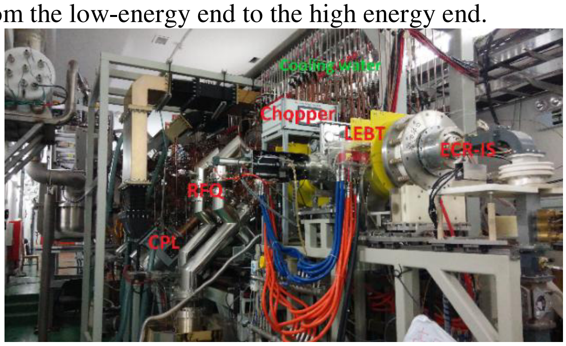

Figure 2: Photograph of the LEBT and RFQ.

The beam energy was measured with the time of flight method using two fast current transformers (FCT1 and FCT2). The current can measured by the DCCT of MEBT.

The emittance monitor was a conventional double-slit type to measure the transverse emittances of the RFQ. The gap length of the slit was 0.1 mm, and the distance between the upstream slit and the downstream was 433.7 mm. Each slit was driven by stepping motors. According to the measurement, we can reconstructed the beam.

Finally, the beam was directed to the beam dump as bigger beam size as possible about 400 mm. The beam dump consists of two copper plates with an angle of 20 degrees.

TRANSMMION MEASUREMENT

In the commissioning, the results of about 10-mA proton beam experiment are presented and compared with those of the simulation. TraceWin [3] and PARMTEQ [4] were employed for the RFQ simulation.

With the repetition frequency 50 Hz and pulse length 300 us, we have measured the beam transmission efficiency with different input power. The accelerated beam current was obtained by the ACCT at the entrance of RFQ and the DCCT at the MEBT.

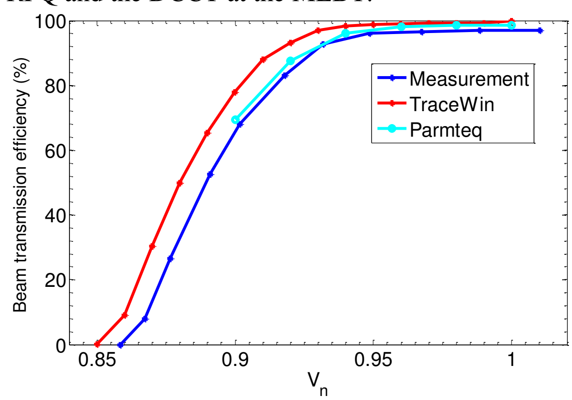

Figure 3: Measured and simulated transmissions of RFQ as functions of the inter-vane voltage V_n.

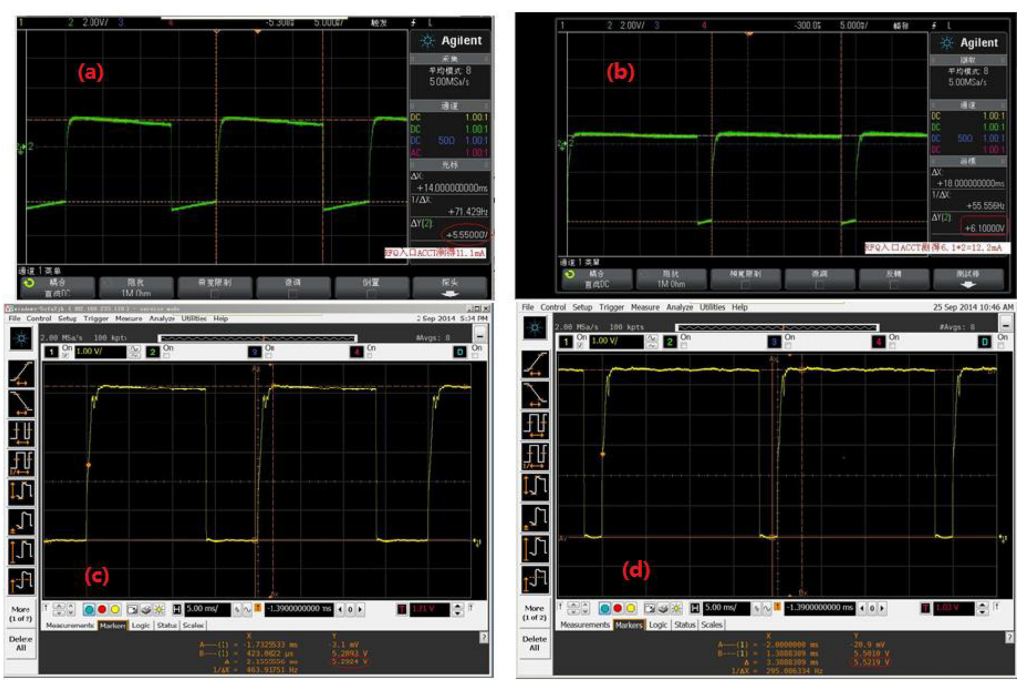

Figure 4: Beam transmission efficiency at high duty factor. (a) beam current measured by ACCT at 70% duty factor; (b) beam current measured by DCCT at 70% duty factor; (c) beam current measured by ACCT at 90% duty factor; (d) beam current measurment by DCCT at 90% duty factor.

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Figure 3 shows the inter-vane voltage dependence of the transmission through the RFQ. *Vn* denotes the inter-vane voltage of the RFQ normalized to the nominal voltage (55 kV), and the vertical axis is the transmission. The measured and simulated transmissions of the accelerated particles are almost consistent. The simulated transmissions by TraceWin are larger than the measurement results and the simulated transmissions by PARMTEQ are closer to the measurement results.

We also finished some beam test with high duty factor, shown in Fig.4. At 90% duty factor, we got 11 mA 31 kW proton beam at RFQ exit with 90% beam transmission efficiency, while 95% beam transmission efficiency at 70% duty factor. The transmission efficiency is lower with higher duty factor, which maybe is because that higher duty factor caused higher temperature rise of cooling water at the end of RFQ and then bigger frequency shift.

EMITTANCE MEASUREMENT

The emittance monitor was a conventional double-slit type to measure the transverse emittances of the RFQ. To prevent melting of the edge of the slits, the emittances of the 10-mA beam were measured with a width of 100 μs and a repetition rate of 10 Hz. For the simulation, the input twiss parameters of RFQ was got from the beam test of LEBT, where the normalized rms emittance is 0.14 π mm-mrad. The beam energy was measured as 3.19 MeV with the time of flight method.

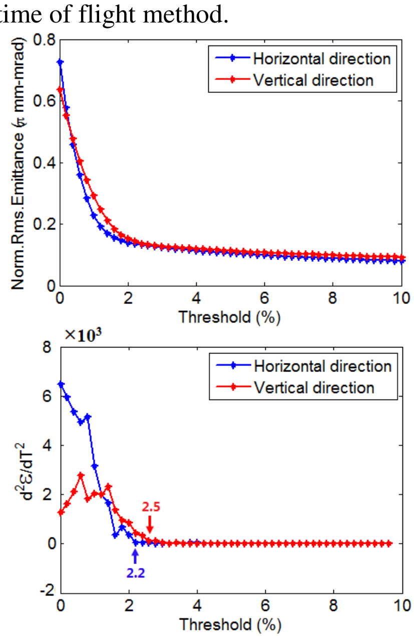

Figure 5: Emittances and the second derivative of emittance as functions of threshold of signal.

The noisy of measured signal will affect emittance measurement greatly, so we should analysis the influence of noisy to get reasonable measurement results. Figure 5 shows emittance as functions of threshold of signal in transverse planes. Here we proposed a new method to decide the threshold: one get the second derivative of emittance as functions of threshold $d^2\varepsilon/dT^2$, then get a threshold to make this value close to zero or very small compare with smaller thresholds, which one is the threshold we wanted and we will get the emittance and twiss parameters. According to the analysis shown in Fig. 5, we got the threshold is 2.2 % in horizontal direction and 2.5% in vertical direction. In Fig. 6, the upper row shows the simulation transverse emittances and the lower row gives the measured results. The measured values of the normalized rms transverse emittances in the horizontal and vertical planes were almost same 0.135 π mm-mrad, whereas the simulated emittances were 0.144π mm-mrad and 0.147 π mm-mrad, respectively. The simulation well reproduces the measurements.

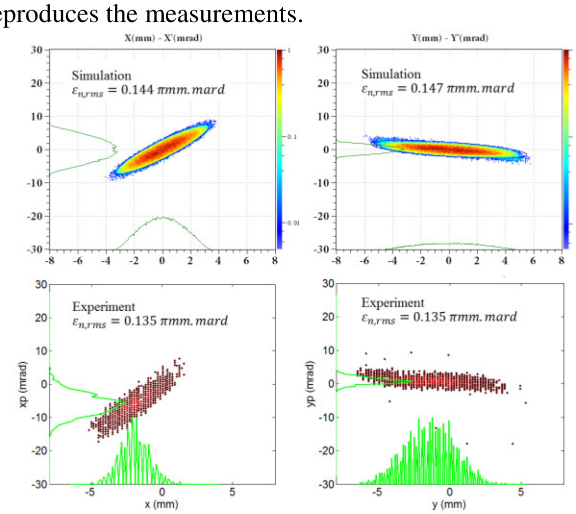

Figure 6: Simulated (upper) and measured (lower) transverse emittances and beam distribution of the RFQ.

CONCLUSION

The test stand composed of an ECR ion source, LEBT, RFQ, MEBT and beam dump have been installed and the first stage of beam commissioning have been finished at IHEP. We have measured the beam transmission efficiency with different input power, which is basically same as simulation results. The energy after RFQ was measured as 3.19 MeV by TOF method with FCTs. The transverse emittance measured by double-slits emittance meter was 0.135 π mm-mrad.

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